Applied Energy 228 (2018) 1994–2008

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

# The impact of the expansion in non-fossil electricity infrastructure on China's carbon emissions

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## HIGHLIGHTS

- Multi-regional carbon impacts of non-fossil electricity investments are explored.
- Investment impacts are compared with operational impacts.
- Spillover effects of non-fossil electricity investments are investigated.
- Investment impacts are negligible relative to operational impacts.
- Developed regions outsource investment impacts to developing regions.

## ARTICLE INFO

*Keywords:*
$CO_2$ emissions
Non-fossil electricity
Investment
Multi-regional input-output model

## ABSTRACT

In recent years, China has embarked upon an ambitious roll-out of non-fossil electricity investments. This has led to substantial impacts on carbon emissions, which is expected to continue into the future. However, non-fossil electricity has a significant carbon footprint in pre-operation activities, which we term investments (in the form of the construction, transportation and assembly of electricity generators). This paper addresses two main questions: (1) How do non-fossil electricity investments impact $CO_2$ emissions in China? and (2) How are such impacts distributed within China? To answer these questions, we use a hybrid, multi-region, input-output (MRIO) model to assess the emission impacts of investments compared with impacts during the operation of generators. As there was a large surge in the installed capacity during the analysis period (2002–2010) we considered a counterfactual scenario in which non-fossil electricity expansion did not occur, and where generation followed historical patterns (i.e. using fossil energy). Results indicate that non-fossil electricity investments resulted in a net emission increase of 16.21 Mt, 28.71 Mt and 47.29 Mt in 2002, 2007 and 2010 respectively, while the net emission reduction during the operational phase of electricity generation was, respectively, 48.84 Mt, 81.83 Mt and 129.48 Mt per year. Non-fossil electricity investments led to a significant increase of emissions in the northern, northeastern and northwestern regions due to a rapid development of wind power. In general, due to supply chains, developed regions (e.g. east China) outsource the carbon impacts of non-fossil electricity investments to developing regions (central and north China). The carbon impacts of non-fossil electricity investments are often transferred to adjacent regions.

## 1. Introduction

The surface temperature of the earth has risen by nearly a degree over the past century [1]. In response, the international community reached the world's most significant agreement to address climate change (the Paris Agreement) in December 2015 [2,3]. In China, a series of measures to address carbon emissions have been implemented [4]. Among these, the 13th Five Year Plan (2016–2020) set a target to reduce the carbon intensity of energy production by 18% by 2020 compared to the 2015 level [5,6]. In the Intended Nationally Determined Contribution (INDC) released on June 30, 2015, the Chinese government proposed a target of raising the share of non-fossil energy sources in primary energy consumption to 20% by 2030 [7]. To facilitate this, China's 13th Five-Year Development Plan (2016–2020)

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https://doi.org/10.1016/j.apenergy.2018.07.069
Received 26 January 2018; Received in revised form 16 June 2018; Accepted 14 July 2018
Available online 21 July 2018

provided an investment of 2500 billion yuan in NE through to 2020 [8]. It is important to assess the carbon emissions associated with these investments.

Against this background, Dai et al. [9] discussed the environmental co-benefits of NE investments in China by 2050 using a Computable General Equilibrium (CGE) model, concluding that NE substantially reduced carbon emissions. The study is restricted to China as a whole and does not model the spatial difference of impacts of investments between provinces. Dai et al. [9]'s analysis does not investigate the historical carbon impact of China's NE investments. However, the historical carbon impact of China's NE investments should not be ignored, especially considering that China's NE investments totaled $110 billion in 2015, accounting for more than 33% of the global NE investments totalling $329 billion [10].

To provide insights into the environmental impact of historic NE investments, we present a multi-region, multi-period investigation. We construct a counterfactual scenario, in which NE investments did not take place, and were replaced by thermal power to satisfy an exogenous electricity demand (following the approach of Behrens et al. [11]). This provides useful policy implications for China's future emission reduction, as there was a substantial increase in installed NE capacity in the period under study. Since NE investments have a long-term impact on operational-phase emissions of power generation due to the long lifetime of generators, we not only analyze the impact of NE investments, but also compare it with the carbon impact of the operational phase. In order to quantify their separate contributions across Chinese provinces, we present an alternative methodological framework based on MRIO models. A limitation of using Chinese MRIO tables for energy system investigations is that NE sectors are not disaggregated. We overcome this limitation by creating vectors of demand that include the various sectors comprising NE infrastructure, but not by disaggregating the MRIO itself (due to parametric and systematic error as described in Wiedmann et al. [12], and Lindner et al. [13]. Using this demand-driven MRIO model based on consumption-based accounting, we explore how NE investments impacted past emissions from both intraregional and interregional perspectives. Then, we further hybridize the MRIO table by disaggregating the electricity sector by fuel types to investigate the carbon impact of the operational phase of NE generation. This hybrid system has a disaggregated electricity sector in energy units, which generates electricity for the aggregated electricity sector in the MRIO in monetary units. This is a crucial step forward for the MRIO disaggregation of the Chinese electricity system and will better aid policy development.

This paper is organized as follows. Section 2 summarizes previous relevant research. Section 3 describes methods and data sources. The results are presented in Section 4 and discussed in Section 5. Section 6 concludes the paper.

## 2. Literature review

### 2.1. The environmental impact of China's NE development

The environmental impact of NE generation in China has attracted significant attention. Qi et al. [14] estimated the energy and $CO_2$ emission impact of renewable energy (RE) development in China. Long et al. [15] quantified the relationship between energy consumption, carbon emissions, and economic growth during the period 1952–2012. Li et al. [16] applied Pinch Analysis to estimate the impact of renewable electricity on the Chinese emission target. Mitta et al. [17] estimated RE impacts on carbon emissions and mitigation costs to 2030. Wu et al. [18] used a multi-regional CGE model to investigate carbon impacts of two types of renewable support schemes. Duan et al. [19] developed a technology-driven endogenous economic growth model to assess the carbon impact of wind power. Ito [20] examined the relationship between $CO_2$ emissions, RE consumption, non-RE consumption and economic growth during 2002–2011. Yuan et al. [21] built a MRIO model to investigate the impact of NE development on emissions embodied in exports. These results generally indicated that NE development can help achieve carbon emission reductions in an efficient manner. However, previous studies generally investigate the operational phase only, the phase in which electricity is being generated, and do not capture the impact of NE investments on $CO_2$ emissions (i.e., emissions resulting from the construction of the NE equipment itself, its transport and installation).

### 2.2. The environmental impact of NE investments

There are a growing number of studies exploring the environmental implications of NE investments at national and/or regional levels. Above we highlighted that CGE and IO models are common tools for such analyses from a macroeconomic perspective. In contrast to the MARKAL family of energy system models [22,23], and hybrid Life Cycle Assessment models [24,25], these approaches model the impact of NE investments by including interrelationships between the NE sector and other economic sectors. CGE models can show how an economy reacts to a change in a particular policy or technology in a dynamic way. However, the method requires abundant data, as cost and economic parameters for various energy technologies are required [26]. Case studies representing CGE models include Yahoo and Othman [27] as well as Yamazaki and Takeda [28]. An influential CGE study [9] concluded that large-scale NE investments would generate a net reduction of 61 Gt $CO_2$ from 2010 to 2050. However, this study focuses on the impacts of a future evolution of NE investments, and does not assess the impacts of historical investments. Furthermore, the study only considers the impact of NE investments at a national level and does not provide disaggregated results per province. It remains unclear how impacts are distributed within China. This is important because, as case studies of wind investments in Germany shows [29], NE impacts differ across regions.

CGE models are generally not available for multi-regional impact analysis, as the availability of cross-regional economic data is limited. MRIO models have the advantage of representing transactions between several countries/regions and their corresponding economic sectors using readily available data [30]. This makes them suitable for the assessment of cross-national/regional impacts. Additionally, IO is based on actual observations of trade among the sectors and can be used to study the short-term impact of a demand stimulus [31]. Research using this approach has generally focused on the economic and employment impacts of NE investments. For example, Caldes et al. [32] focused on the economic impact of the investment in solar thermal electricity. De Arce et al. [33], Lehr et al. [34] and Markaki et al. [35] analyzed the economic impact of RE investments in Morocco, Germany, and Greece. Chun et al. [36] used IO analysis to project the impact of hydrogen investment on the Korean economy during 2020–2040. Varela-Vazquez and Sanchez-Carreira [37] investigated the socioeconomic impact of wind investment in peripheral regions. Lehr et al. [38] used an IO model to investigate the impact of RE investments on the labor market. Tourkolias and Mirasgedis [39] and Oliveira et al. [40] estimated the employment benefits of RE investments in Greece and Portugal. Simas and Pacca [41] and Okkonen and Lehtonen [42] assessed the employment impact of wind investment in Brazil and Northern Scotland. Ortega et al. [43] calculated employment effects of RE deployment in the European Union in the 2008–2012 period. Dvořák et al. [44] explored the relationship between RE investments and job creation in the Czech Republic referring to EU benchmarks. Garrett-Peltier [45] compared the employment impact of increasing energy efficiency and the use of RE in the United States. Although these papers focus on economic impacts, the mechanics of studying different types of impacts are not very different, so there is a strong theoretical background to the model constructed and developed in this work.

The environmental impacts of energy policies and investments in other, developed countries have been analyzed using IO models.

Madlener and Koller [46] used IO to estimate the economic and carbon reduction impacts of bioenergy development. Ritchie and Dowlatabadi [47] adopted an IO-LCA to assess the environmental impact of a fossil fuel divestment strategy. Choi et al. [48] used a community-economic IO model to estimate the economic and environmental impacts of energy efficiency investment. Choi et al. [49] calculated the environmental impacts of a new gasoline tax coupled with bio-subsidies. Medina et al. [50] assessed the environmental benefits of energy efficiency investment in Spain. Behrens et al. [11] estimated the environmental impact of NE investments in Portugal. Medina et al. [50] illustrated the importance of investment activities by evaluating the changes of direct and indirect $CO_2$ emissions. Lucchesi et al. [51] applied an IO model to estimate the environmental impacts of electricity investment in Brazil. The bulk of literature from China's IO research looks at the jobs and incomes generated from NE investments. For example, using an environmentally-extended IO framework, Lee et al. [31] illustrated the economic and environmental implications of energy polices. Cai et al. [52] studied the environmental, economic and social impacts of the infrastructure of RE during 2000–2010 with a hybrid IO model. Yuan et al. [53] projected the impact of low-carbon electricity investment expansion in China up to 2040.

To the best of our knowledge, no existing IO approach has been used to evaluate the historical environmental impact of NE investments in China. Moreover, no studies have investigated the interaction mechanisms through which the environmental impact of NE investments propagate across regions in China. The research gap also includes the extent to which spillover effects are caused by NE investments, although regional spillovers necessarily correspond to embodied environmental impacts that occur in all third-party regions from investment demand [54]. Additionally, previous IO analyses do not compare the carbon impact of NE investments with the carbon impact estimates of NE operation, as no studies link an IO table in monetary units with electricity generation data in physical units as we do here.

## 3. Methods and data

### 3.1. Methods

#### 3.1.1. Introduction

Following the analysis of Behrens et al. [11] and Usubiaga et al. [55], we determine the net emissions resulting from the expansion in NE infrastructure compared against a counterfactual scenario where the expansion did not take place. Here we divide the environmental impacts from NE into two parts: the investment phase and the operational phase. The former accounts for the $CO_2$ emissions that result from the installation of new NE infrastructure (e.g. the manufacture of wind turbines, transportation to the wind farm, and assemblage); the latter accounts for the change of $CO_2$ emissions associated with structural changes in the China's electricity mix. The counterfactual scenario assumes that the newly installed NE capacity is replaced by thermal power (coal, oil, and natural gas), but all other settings, including power demand, are the same as in the reference scenario.

Since we assume that electricity production in both scenarios is the same, the installed capacity ($m$) and electricity generation ($g$) of thermal power in the counterfactual scenario is calculated by

$$m_1^{alt} = m_1^{ref} + \sum_{i=2}^{5} m_i^{ref} \times \frac{h_i}{h_1} \tag{1.1}$$

$$g_1^{alt} = g_1^{ref} + \sum_{i=2}^{5} m_i^{ref} \times h_i \tag{1.2}$$

where the index $i = 1, \ldots, 5$ refers to the various electricity technologies in a specific order: thermal, hydro, nuclear, wind and solar power; $m$ is the amount of new installed capacity; $g$ is the amount of electricity production; $h_i$ is the annual usage hours of NE technology $i$ (equaling to the annual electricity generation of $i$ in kWh divided by its annual installed capacity in kW), $h_i/h_1$ acts a conversion factor from technology $i$ to thermal power generation to keep the same amount of electricity production between reference and counterfactual scenario. The relative weight of the different technologies in the counterfactual electricity mix is calculated by assuming that the quantity of NE of the preceding year remains constant and thermal power increases as described in Eqs. (1.1) and (1.2).

#### 3.1.2. Additional $CO_2$ emissions due to NE investments by Chinese region

Two methods are commonly used to estimate the carbon impact of NE investments: one is a process analysis (bottom-up approach), which focuses on carbon flows in a series of NE infrastructure processes, and the other is the IO model (top-down approach), which represents the complete supply chain of economic activity [56]. Process analysis, which is relatively straightforward and based on process detail, is more easily understood than IO models. However, process analysis mostly focuses on direct emissions, typically neglecting the indirect emissions in upstream industries [57]. IO models can evaluate emissions across the whole supply chain. Thus, we employ a MRIO model, which distinguishes interregional and intraregional transactions [58] between 21 sectors in 30 Chinese regions, and calculate the impact of NE investments on $CO_2$ emissions in total and by region in China. Note that we quantify the carbon impact of investment specifically in NE infrastructure (e.g. construction of a power plant, and the purchase and installation of equipment). Due to data limitations, investments in the general electricity grid, such as large-scale transmission projects and distribution systems are not included in the analysis, as neither are the final disposal stage of NE facilities and equipment.

The basic Leontief model (Eq. (2)) calculates the change in sectoral $CO_2$ emissions ($MtCO_2$), $\Delta q$, as:

$$\Delta q = BL\Delta y \tag{2}$$

where $B$ is a row vector of $CO_2$ emission coefficients expressing emissions ($MtCO_2$) per unit of economic output (million yuan) of each sector; $L = (I - A)^{-1}$ is a Leontief inverse matrix, and $A$ is the technical coefficient matrix (expressing which inputs from other sectors are required to generate a unit of output of a given sector); and is a vector of an exogenous final demand stimulus, in our case the volume of investments in an electricity technology (e.g. wind, solar).

We use Eq. (2) as a starting point to estimate the carbon impact of NE investments, but because the classification scheme employed in China's MRIO tables does not include electricity sub-sectors, we follow the method developed by Garrett-Peltier [45]. This method requires the quantification of the magnitude of new economic activities associated with NE investments. can be viewed as an exogenous change imposed on the different sectors in the MRIO table. It is defined as $\Delta y\hat{S}V$, the product of a vector of investment scale ($V$) of an electricity technology and a diagonal matrix of input share ($S$) that represents the investment cost structure of a given electricity technology. In other words, $S$ gives the shares of investment by different sectors for a particular energy technology and $V$ is the total amount of investment in that technology. To give an example, nuclear power investment in a region is of scale $v_1$ and the production recipe of nuclear power in a two-sector economy is $s_1$ and $s_2$, respectively. The new demand for products from sector 1 and 2 resulting from the investment in nuclear power is $\Delta y_1 = \begin{bmatrix} v_1 s_1 \\ v_1 s_2 \end{bmatrix}$.

However, the low resolution of China's MRIO tables can pose problems, as emissions data refers to the average of sub-products in the aggregated sector [59]. Further explorations can be found in Su and Ang [60], Matumoto and Hondo [61], Wiedmann et al. [12] and Rocco et al. [62]. For example, if there is a 10 million yuan investment in solar, an MRIO approach will consider this additional demand as spread over the outputs of the existing sectors in MRIO tables (e.g. the electronic equipment sector). This means that, constrained by aggregated sector representation, some additional demand for solar investments from process-specific data (e.g. the silicon due to the production of solar panels) is distributed using economy-side data of the MRIO analysis. In theory, a disaggregation of MRIO table is possible, however, due to the limitation of data available, it is difficult to collect process-specific data for a disaggregated analysis. Thus, we assume that the process-specific demand for upstream activities of NE investments is distributed among all the intermediate inputs between sectors. For example, the additional demand for silicon in the production of solar panels is allocated to the non-metal material sector.

Consumption-based accounting is used to estimate the regional carbon impact of NE investments. The analysis is performed separately for each technology in each region. Thus, the impact of investment in an electricity technology ($\Delta q$) in a region is:

$$\Delta q = \hat{B} L \hat{S} \hat{V} \tag{3}$$

The MRIO model comprises of $n_R$ regions, each of them with $n_S$ economic sectors. $\Delta q$ is the resulting matrix of sectoral emissions with sides of length $n_R n_S$. $B$ is a diagonal matrix of environmental intervention coefficients with sides of length $n_R n_S$. $L$ is a square Leontief inverse matrix with sides of length $n_R n_S$. To discriminate the impact of NE investment across all regions, the investment scale and share matrix are reframed as follows. $S$ is a diagonal input share matrix, expressing the input weights of sectors that exist within the MRIO tables and describing the production recipe of investment in a particular electricity technology; $V$ becomes a diagonal matrix, containing the investment scale (million yuan) in a given electricity technology in a given region where investment occurs whereas other regions are set to zero.

It is important to note that we assume that the investment cost structure of an electricity technology, that is, the input share matrix $S$, for different periods and regions are identical. This assumption is reasonable, as in view of the medium term (2002–2010) horizon of this study, the investment cost structure is unlikely to change quickly. Moreover, the technology of electricity installation is relatively mature and can be assumed to remain unchanged nationwide [63]. Now, it is possible to distinguish two different $CO_2$ effects associated with electricity investment. The first is the intraregional effect, representing one region's $CO_2$ emissions induced by domestic electricity investments. The second is the interregional spillover effect, one region's $CO_2$ emissions caused by another region's electricity investments, propagated along supply chains.

In order to make meaningful comparisons across time and regions we do not report carbon intensity values in monetary terms, but in energy terms. That is, we will examine the emissions per unit of installed capacity ($MtCO_2$/GW), $p$, defined as:

$$p_{r,i} = \Delta q_{r,i}/m_{r,i} \tag{4}$$

where $r$is an index referring to one of the 30 provinces $p$ and the total net impact of NE investments ($\Delta q_{inv}$) is the amount emissions that have been produced in the reference scenario minus the total emissions that would have been produced in the counterfactual scenario. For each scenario, emissions equal the amount of new installed capacity ($m$) multiplied by the $CO_2$ emission coefficient ($p$). Thus,

$$\Delta q_{inv} = \sum_r \sum_i p_{r,i} \times m_{r,i}^{ref} - \sum_r \sum_i p_{r,i} \times m_{r,i}^{alt} \tag{5}$$

### 3.1.3. Reduction in operational $CO_2$ emissions due to expanded NE capacity

The operational emissions from NE are calculated using the theoretical framework developed by Guevara and Rodrigues [64] and Yuan et al. [53], in which an energy-economy, sequential hybrid model is used to combine the MRIO model (in which there is a single electricity sector) with more detailed energy data on each particular electricity technology. The vector of direct emission coefficients is now decomposed in four separate terms, with the full Leontief model becoming:

$$q = CFTELy \tag{6}$$

Let $n_R$ be the number of regions, $n_S$ be the number of sectors, and $n_F$ the number of fuel types. y is a column-vector of final demand of length $n_R n_S$, with nonzero values in estimated region and the remaining values empty; $E$ is a matrix with $n_R$ rows and $n_R n_S$ columns, referring to the electricity intensity of each sector in each region (in kWh/yuan); $T$ is the matrix of interregional electricity transmission [65], with $2n_R$ rows (to distinguish production for domestic use and for interregional transmission) and $n_R$ columns giving the electricity output that required by itself and other regions; $F$ is the fuel use matrix with $2n_R$ columns and $2n_R n_F$ rows, describing the electricity mix in each region (the factor 2 in the number of rows and columns is required to distinguish electricity production for intraregional consumption and for interregional transmission); finally, $C$ is a carbon emissions matrix with $n_R$ rows and $2n_R n_F$ columns giving the emission intensity of different electricity technologies in each region (in $MtCO_2$/kWh).

For ease of visualization, take an example of Eq. (6) which has three sectors (s1, s2 and s3, in which s3 is electricity sector), two regions (r1 and r2) and two fuel types (f1 and f2), for which we have a 4 × 6 carbon coefficient matrix (C), a 6 × 4 fuel mix matrix (F), a 4 × 2 electricity transmission matrix (T), a 2 × 6 electricity intensity matrix (T), a 6 × 6 Leontief matrix (L) and a 6 × 1 final demand matrix (Y), in which the stimulus takes place in the first region. Note that the non-zero elements in Eq. (7.3) distinguishes between electricity output for domestic use and interregional transmission. Since the electricity sector is described separately from the rest of the economy, the rows and columns corresponding to the electricity sector in Eqs. (7.4) and (7.5) need to be set to zero to avoid double counting [66]. The information for C F T E L and Y can be arranged as:

$$C = \begin{vmatrix} C_{f1}^{r1} & C_{f2}^{r1} & & & & & & \\ & & C_{f1}^{r1} & C_{f2}^{r1} & & & & \\ & & & & C_{f1}^{r2} & C_{f2}^{r2} & & \\ & & & & & & C_{f1}^{r2} & C_{f2}^{r2} \end{vmatrix} \tag{7.1}$$

$$F = \begin{vmatrix} F_{f1}^{r1} & & & \\ F_{f2}^{r1} & & & \\ & F_{f1}^{r1} & & \\ & F_{f2}^{r1} & & \\ & & F_{f1}^{r1} & \\ & & F_{f2}^{r1} & \\ & & & F_{f1}^{r1} \\ & & & F_{f2}^{r1} \end{vmatrix} \tag{7.2}$$

$$T = \begin{vmatrix} T^{r1r1} & \\ & T^{r1r2} \\ & T^{r2r2} \\ T^{r2r1} & \end{vmatrix} \tag{7.3}$$

$$E = \begin{vmatrix} E_{s1}^{r1} & E_{s2}^{r1} & 0 & & & \\ & & & E_{s1}^{r2} & E_{s2}^{r2} & 0 \end{vmatrix} \tag{7.4}$$

$$L = \begin{vmatrix} L_{s1s1}^{r1r1} & L_{s1s2}^{r1r1} & 0 & L_{s1s1}^{r1r2} & L_{s1s2}^{r1r2} & 0 \\ L_{s2s1}^{r1r1} & L_{s2s2}^{r1r1} & 0 & L_{s2s1}^{r1r2} & L_{s2s2}^{r1r2} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ L_{s1s1}^{r2r1} & L_{s1s2}^{r2r1} & 0 & L_{s1s1}^{r2r2} & L_{s1s2}^{r2r2} & 0 \\ L_{s2s1}^{r2r1} & L_{s2s2}^{r2r1} & 0 & L_{s2s1}^{r2r2} & L_{s2s2}^{r2r2} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix} \tag{7.5}$$

$$Y = \begin{vmatrix} y_{s1}^{r1} \\ y_{s2}^{r1} \\ y_{s3}^{r1} \\ 0 \\ 0 \\ 0 \end{vmatrix} \quad (7.6)$$

Based on Eq. (6), the net operational impact of NE ($\Delta q_{ope}$) is quantified as:

$$\Delta q_{ope} = CF^{ref}TELy - CF^{alt}TELy \quad (8)$$

An important difference between investment and operational impacts is the time frames considered. The impact of investment is localized in a single year (or a few years, if the implementation of the project is complex and has a longer duration), while the operational impact will last for the lifetime of the installation. Hence, the operational impact of NE will continue after 2010, taking place over the entire project period [11].

Note that for the purpose of this analysis we will not look into the carbon intensity of the operational phase and hence no analogue of Eq. (4) will be developed here. Note also that there are alternative approaches to disaggregating the electricity sector by disaggregating the MRIO itself (as described by Lindner et al. [67], Lindner and Guan [68] and Wang [69]. However, the disaggregation of the IO table does result in parametric and systematic errors, as there are a range of possibilities for the unknown technical coefficients in the disaggregated IO table [12,13]. In order to minimize error in this study, we develop a hybrid system, with a disaggregated power sector in energy units, which generates electricity for the aggregated MRIO electricity sector in monetary units. This is possible because every electron is 'equal', that is, all the energy in electrical power generation goes to make the same product. According to this approach, the operational impact of NE can be investigated by calculating the changes in proportions of different energy types to the total energy consumption in the same physical unit.

### 3.2. Data

The MRIO tables of China's 30 provinces for 2002, 2007, 2010 are obtained from Shi and Zhang [70], Liu et al. [71], and Liu et al. [72], respectively. The 30 sectors listed in 2007 and 2010 tables and the 21 sectors listed in the 2002 table are aggregated to 21 sectors to have consistent tables for 2002, 2007 and 2010 (as shown in Table A1 in Appendix). Therefore, we work under the supposition that in many cases, the ratio of domestic products and imports during the input of each type of good to be constant.

We use official data, including the history of cement production and the consumption of energy and electricity, to estimate sectoral $CO_2$ emissions. We consider emissions from cement production (an emissions-intensive process [73]) because cement is a major input in the construction of some energy types (high importance for hydropower and nuclear, medium importance for wind turbines and low importance for solar). We adopt the IPCC [74] sectoral approach to calculate $CO_2$ emissions. $CO_2$ emissions equal activity data (fossil fuel consumption and cement production) multiplied with carbon emission factors. The activity data of fossil fuels for 2002, 2007 and 2010 are collected from the Provincial Energy Balance Tables reported by *China Energy Statistics Yearbook* [75,76,77]). Until now, the Provincial Energy Balance Tables of China for regional fossil fuel consumption are only available at an aggregated sectoral level. We use the approach of Zhang et al. [78], to disaggregate energy balance tables to match MRIO tables by referring to the sub-sectoral fossil fuels consumption from *Provincial Statistical Yearbooks* of China's 30 provinces [79–81]). The data on annual cement production are collected from the *China Statistical Yearbook* [82–84]). Carbon emission factors for fossil fuels (tonne $CO_2$/tonnes, $m^3$) and cement production (tonne $CO_2$/ tonnes) are collected from IPCC [74] and NDRC [85]. For verification, we compare the resulting total $CO_2$ emissions in our IO model with other estimates. Over the three years of our analysis, our emission estimates were 1–4% lower than those reported in Emissions Database for Global Atmospheric Research (EDGAR) [86], and 10–15% higher than the Energy Information Administration (EIA) [87], Carbon Dioxide Information Analysis Center (CDIAC) [88] and BP estimates [89]. The agreement across different $CO_2$ emission accounting approaches provides confidence in the reliability of aggregated emission estimates.

The provincial investment scale of different electricity technologies (e.g. the scale of investment in nuclear power infrastructure in a province) comes from the *China Electric Power Yearbook* [90,91,92] and *Annual development report of China's power sector* [93,94,95]. The investment structure of NE (e.g. the production receipt of nuclear power infrastructure) is sourced from Dai et al. [9], and the data for thermal power is collected from *Cost and Performance Baseline for Fossil Energy Plants* [96]. Table A3 summarizes this information, harmonized to the sector classification used in this study.

The data of electricity capacity and generation are collected from *China Electric Power Yearbook* [90,91,92]. Electricity transmission data for provincial grids in 2007 and 2010 are from the *Annual Report of Power Market Transactions* [97,98]. Electricity transmission data for provincial grids in 2002 are from CEPYEB [90].

As illustrated in Fig. 1, in 2002, NE comprised 26.9% of total, newly installed capacity (in MW), with the largest increases in nuclear and hydropower representing 16.5% and 10.3% of the total respectively. In 2007, installed wind capacity started to increase, amounting to 3.0% of the total. The installed nuclear capacity accounted for 2.0% of the total. From 2007 to 2010, the installed wind capacity continued to increase at a rapid rate, reaching a peak of 16.0% of the total by 2010. The new installed hydropower capacity increased by more than 5%. The share of solar power in new capacity was only 0.20% of the total in 2010. Fig. 1 also shows which provinces most contributed to the new NE capacity in 2010. Sichuan led with new hydropower capacity of 3.97 MW followed by Yunnan (3.63 MW), Guizhou (2.33 MW) and Qinghai (2.03 MW). Zhejiang (9.10 MW) and Guangdong (5.45 MW) contributed the most to the new capacity of nuclear power. The new capacity of wind in Inner Mongolia, Hebei, Gansu, and Liaoning was respectively 4.31 MW, 2.09 MW, 1.70 MW and 1.2 MW, accounting for 60% of the total. Over 71% of newly installed solar was concentrated in Jiangsu (71 kW) and Ningxia (58 kW).

## 4. Results

The organization of the results is as follows: Section 4.1 presents the distribution of $CO_2$ emissions in China's 30 provinces; Section 4.2 shows the importance of investment impacts when compared to operational impacts in both historical and counterfactual scenarios; Section 4.3 shows how the carbon performance (measured in $MtCO_2$/GW) of installing different energy types evolved across Chinese regions, and uses this information to assess the investment impact of the observed expansion in NE infrastructure; finally, Section 4.4 assesses the role of supply chains in impacts of NE expansion.

### 4.1. $CO_2$ Emissions in China

According to our emission estimates, during 2002–2010, total $CO_2$ emissions in China increased by 119%, with an absolute increase of 4.88 Gt $CO_2$ (see Table 1). The largest provincial increases were in Shandong, Inner Mongolia, Hebei, Jiangsu and Guangdong, contributing to 10.9%, 7.7%, 7.1%, 6.9% and 6.4% of the overall national growth, respectively. The distribution of province-level emissions developed over time. In 2002, Hebei (318 Mt), Shandong (313 Mt), Guangdong (266 Mt), Jiangsu (258 Mt) and Shanxi (245 Mt) were the biggest five provincial $CO_2$ emitters. Between 2002 and 2007, Henan's emissions increased by 93.4%, and the top five emitters became Shandong (769 Mt), Jiangsu (572 Mt), Guangdong (535 Mt), Hebei

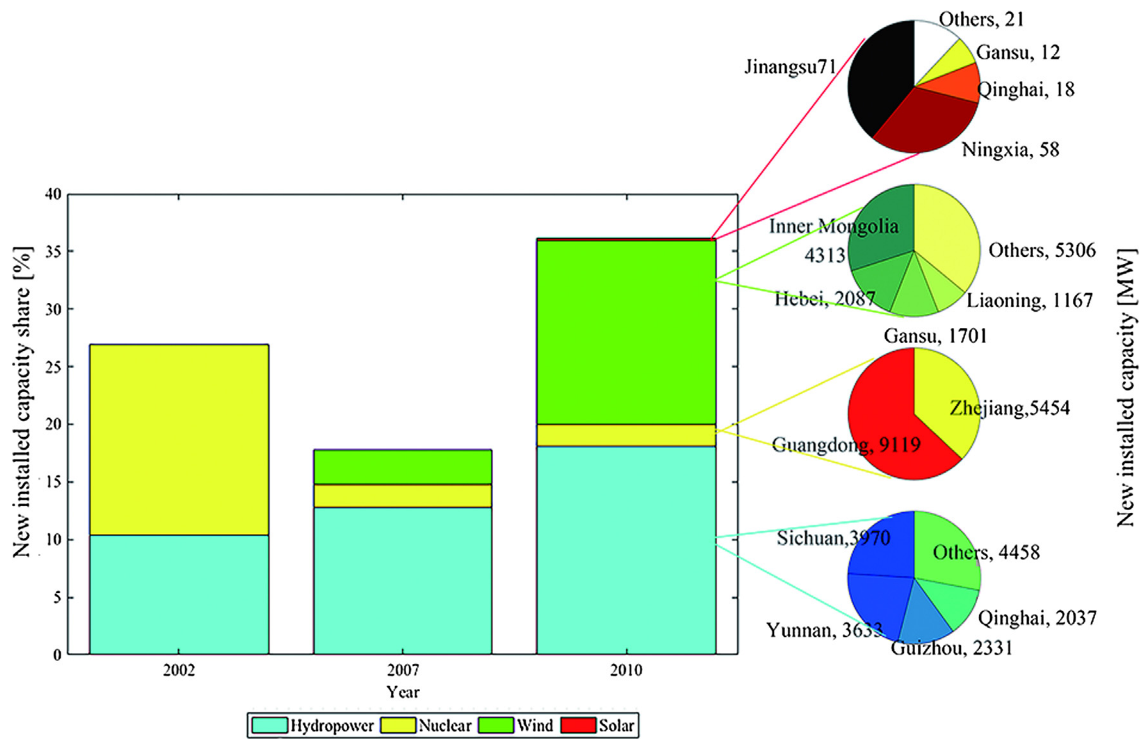


**Fig. 1.** The evolution of China's NE investments.

(517 Mt), and Henan (432 Mt) by 2007. In 2010, the share in total emissions of Shandong (9.4%), Jiangsu (6.6%) and Guangdong (6.4%) decreased while that of Hebei (7.4%) continued increasing. The combined share of the five major emitters (Shandong, Hebei, Jiangsu, Guangdong and Shanxi) made up 35.7% of total national emissions. Overall, Shandong, Hebei, Jiangsu, Guangdong, Henan and Shanxi held sizeable shares of national total emissions, and Inner Mongolia played an increasingly important role.

**Table 1**
The $CO_2$ emissions and share of national emissions for 30 provinces.

| | 2002 | | 2007 | | 2010 | |
|---|---|---|---|---|---|---|
| | Emissions (Mt) | Emission share (%) | Emissions (Mt) | Emission share (%) | Emissions (Mt) | Emission share (%) |
| Beijing | 86.4 | 2.1 | 143.3 | 1.9 | 112.9 | 1.3 |
| Tianjin | 75.2 | 1.8 | 115.1 | 1.6 | 153.3 | 1.7 |
| Hebei | 317.9 | 7.8 | 516.9 | 7.0 | 663.5 | 7.4 |
| Shanxi | 244.9 | 6.0 | 321.4 | 4.3 | 518.9 | 5.8 |
| Inner Mongolia | 137.4 | 3.4 | 316.4 | 4.3 | 511.5 | 5.7 |
| Liaoning | 232.3 | 5.7 | 372.0 | 5.0 | 469.7 | 5.2 |
| Jilin | 107.5 | 2.6 | 181.0 | 2.4 | 214.4 | 2.4 |
| Heilongjiang | 136.0 | 3.3 | 210.4 | 2.8 | 236.1 | 2.6 |
| Shanghai | 137.4 | 3.4 | 306.5 | 4.1 | 224.8 | 2.5 |
| Jiangsu | 258.3 | 6.3 | 571.9 | 7.7 | 594.5 | 6.6 |
| Zhejiang | 180.8 | 4.4 | 331.1 | 4.5 | 370.4 | 4.1 |
| Anhui | 152.5 | 3.7 | 210.4 | 2.8 | 278.0 | 3.1 |
| Fujian | 78.3 | 1.9 | 166.5 | 2.3 | 204.7 | 2.3 |
| Jiangxi | 71.5 | 1.7 | 133.2 | 1.8 | 151.2 | 1.7 |
| Shandong | 313.3 | 7.7 | 768.9 | 10.4 | 843.0 | 9.4 |
| Henan | 223.6 | 5.5 | 432.4 | 5.8 | 524.1 | 5.8 |
| Hubei | 161.0 | 3.9 | 268.2 | 3.6 | 336.2 | 3.7 |
| Hunan | 112.5 | 2.7 | 232.9 | 3.1 | 266.7 | 3.0 |
| Guangdong | 265.5 | 6.5 | 534.5 | 7.2 | 576.7 | 6.4 |
| Guangxi | 56.8 | 1.4 | 126.6 | 1.7 | 155.1 | 1.7 |
| Hainan | 17.2 | 0.4 | 23.5 | 0.3 | 30.8 | 0.3 |
| Chongqing | 79.1 | 1.9 | 90.3 | 1.2 | 156.6 | 1.7 |
| Sichuan | 145.9 | 3.6 | 210.5 | 2.8 | 305.7 | 3.4 |
| Guizhou | 101.0 | 2.5 | 173.9 | 2.4 | 202.7 | 2.3 |
| Yunnan | 83.3 | 2.0 | 158.0 | 2.1 | 199.0 | 2.2 |
| Shaanxi | 87.4 | 2.1 | 136.7 | 1.8 | 229.8 | 2.6 |
| Gansu | 68.5 | 1.7 | 108.9 | 1.5 | 133.2 | 1.5 |
| Qinghai | 17.2 | 0.4 | 25.6 | 0.3 | 33.0 | 0.4 |
| Ningxia | 64.6 | 1.6 | 68.6 | 0.9 | 103.5 | 1.2 |
| Xinjiang | 79.6 | 1.9 | 139.5 | 1.9 | 171.7 | 1.9 |
| Total | 4093 | 100 | 7395 | 100 | 8972 | 100 |

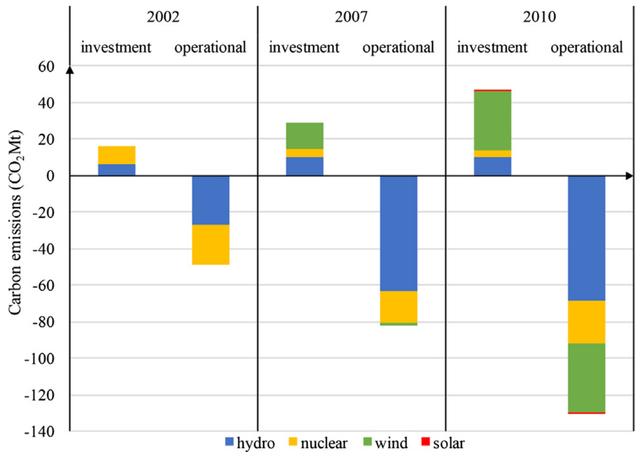


**Fig. 2.** Net investment and operational impacts of NE.

### *4.2. National $CO_2$ impacts of non-fossil electricity investments*

Our study includes emissions from both the investment and operation of electricity generators. Nationally, Fig. 2 shows that between 2002 and 2010, NE investments led to an increase in carbon emissions, but at the same time these investments resulted in a change in electricity mix which reduced emissions in the operational phase. NE investments resulted in a growth in emissions of 16.21 Mt in 2002, 28.71 Mt in 2007 and 47.29 Mt in 2010, while emission reductions derived from NE operation were 48.84 Mt in 2002, 81.83 Mt in 2007 and 129.48 Mt in 2010. These are approximately three times larger than the corresponding figures for investment impacts.

This means that although an expansion in NE infrastructure increases carbon emissions, these increased carbon emissions can be offset by the carbon savings from NE operation in one year. However, this varies between NE type. For hydro and nuclear power, the net carbon impact of investments is smaller than the net operational impact in 2002, 2007 and 2010. In 2007, the net carbon impact of wind investments is larger than its net operational impact, while in 2010, the net carbon impact of wind investments almost equals its net operational impact. This is not necessarily surprising. The carbon pay-back period of NE depends on numerous different factors. Renewable energies can pay back their embodied energy within a year [99,100]. For example, Tahara et al. [101] shows that the carbon payback time of hydropower is less than one year due to smaller carbon emissions from infrastructure. Also, Bush et al. [102] shows that wind power can offset emissions from infrastructure in one year at sites with high wind speeds. However, this does vary, for example, our results show that in 2007, the net carbon impact of wind power investments is larger than its net operational impact. With the increased output of wind power, in 2010, the net carbon impact of wind power investments is smaller than its net operational impact. This result is consistent with the conclusion of Atse et al. [103], who indicates that the higher the output capacity, the shorter the payback period. Thus, the carbon payback time could be reduced as electricity capacity increases.

Moreover, because MRIO tables are only available for 2002, 2007 and 2010 during 2002–2010, we only estimate the carbon impact of NE investments for those specific three years. Although we do not present an evolution of the carbon impact of NE investment in every year, our results still reflect the trend over that period. Note that in a dynamic economy such as China the additional electricity output in a given year does not necessarily reflect the new installed capacity in that single year. This is because the power from the installation in the previous year does not include the power from the installations in the following year. Furthermore, a project might take more than one year to complete. This means that investment operations will be spread over several years. Thus, our underlying working assumption is that all year-on-year evolution is smooth.

In contrast, the operational impact will manifest throughout the life time of the installation, so the carbon benefits are primarily received by society during the operation phase of NE projects. This is because investments in electricity infrastructure have long operational lifetimes, so past investment decisions in China continue to shape electricity mix well into the future, with the total benefits of substituting thermal power generation lasting throughout the lifetime of the NE power project. For example, currently, the average service life of a wind power project is more than 20 years, so a wind power plant built in 2002 will lock in patterns of Chinese electricity output and influence emissions until 2022.

In 2002, nuclear investment had the largest impact at more than 60% of the total. Since 2007, the positive impact of hydropower and nuclear investments decreased significantly, and their share in the total reduced to 21% and 8% by 2010 respectively. The positive impact of wind investment presented significant growth over the period, to almost 70% of the total by 2010. Therefore, wind investments comprised the largest net contribution to emission growth between 2007 and 2010. The positive impact of solar investment was small, accounting for only 1.5% of the total in 2010.

From 2002 to 2010, hydropower had the largest operational impact, although the proportion of the total impact decreased from 77% in 2007 to 53% in 2010. Between 2002 and 2010, nuclear operation also played a leading role in reducing $CO_2$ emissions, resulting in a reduction of 21.48 Mt in 2002, 17.53 Mt in 2007 and 23.46 Mt in 2010. Emission reductions resulting from wind power operation occurred mainly in 2007 (1.24 Mt) and 2010 (37.30 Mt). In 2010, the operational impact of solar power yielded small $CO_2$ reductions (0.08 Mt).

### *4.3. Regional $CO_2$ impacts of non-fossil electricity investments*

We start this analysis by examining the carbon intensity of capacity installed of different energy types (in Mt/GW installed). This can then be applied to look at the difference in carbon impacts of NE technologies over their whole lifetime. We differentiate carbon intensity of installation by province. Fig. 3 shows the carbon intensity of installation for 30 provinces for 2002, 2007 and 2010. Carbon intensities of hydropower installation in the southwestern region decreased continuously. A significant decrease can also be seen in Guangxi and Sichuan. In 2002, hydropower in Guangxi and Sichuan had intensities of 2.04 Mt/GW and 2.13 Mt/GW, respectively, while in 2010 they dropped to 0.67 Mt/GW and 1.00 Mt/GW. Notably, the carbon intensity of installation for wind in the northern region decreased during 2007–2010. The most significant decreases were in Hebei and Inner Mongolia. In 2007 a 1 GW increase in wind power investment led to an additional 3.01 Mt and 3.48 Mt in Hebei and Inner Mongolia respectively, while the same 1 GW allocated to wind power generated only 1.97 Mt and 1.98 Mt of additional emissions in Hebei and Inner Mongolia respectively in 2010. This maybe explained by lower investment costs of hydropower and wind power in the southwestern and northern regions due to good conditions. Additionally, there may be a scale effect, with the investment costs dropping due to a significant amount of cumulative installed capacity in these regions [104]. Moreover, although provinces with a large solar potential are located predominately in the northwestern region, the carbon intensity of installation for solar power in this region is larger than others.

Our counterfactual scenario assumes that the newly installed capacity of NE was replaced by thermal power, with the same total electricity production described in the historical scenario. Because our assessment is performed on various provinces, we highlight the spatial heterogeneity across China. Fig. 4 shows the net investment and operational impacts of NE, compared across provinces. We divide China's 30 provinces into eight larger regions, as shown in Table A2 in the Appendix. In general, for each province, the net impact of NE investments was positive, while the net operational impact of NE was negative.

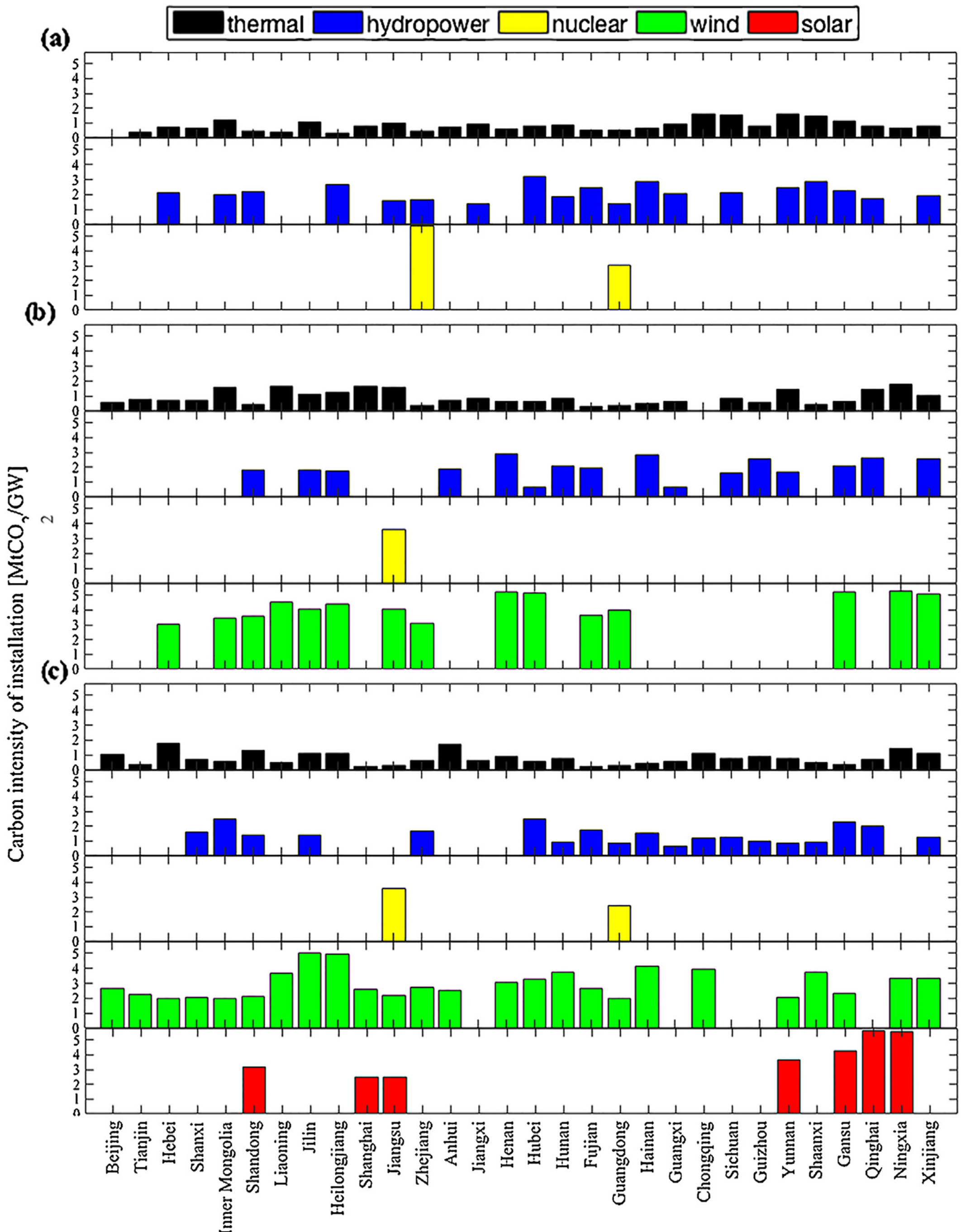


**Fig. 3.** The carbon intensity of installation for various energy types across 30 provinces. Carbon intensity includes all emissions along supply chains which are allocated to the province of installation: (a) 2002; (b) 2007; (c) 2010.

In 2002, Zhejiang had the highest net impact of NE investments, accounting for 47.7% of the total. This impact (7.74 Mt) was larger than that of the net operational reduction (−5.20 Mt). In 2010, the net impact of investments in Zhejiang decreased to 1.83 Mt, while the magnitude of net operational impact grew to −8.65 Mt. This implies that the increased emissions from infrastructure was offset by reductions from operation. Moreover, the magnitude of net investment impacts in other eastern provinces (Shanghai and Jiangsu) were lower that of net operational impacts during 2002–2010. Hence, the deployment of NE will provide continuous reduction of $CO_2$ emissions in the eastern region over the life of the investment. Guangdong played the most significant role in the sharp rise in net operational impacts, accounting for 37.8% of the total in 2002. In 2007, net operational impacts decreased to −15.17 Mt, and deepening to −32.15 Mt in 2010. Compared to operational impacts, NE investments in Guangdong had a relatively small net effect from 2002 to 2010.

In 2002, the southwestern region had a higher net impact of NE investments due to large hydropower developments, accounting for more than 20% of the total net impact. The trend in the net investments for the southwestern region was on the rise between 2002 and 2007. Compared to 2002, the net investments in the southwestern region increased emissions by 69.31% in 2007. Specifically, compared to 2002, Sichuan had the largest increase in net investment impacts by 2007 (877%), followed by Guangxi (655%) and Yunnan (379%). Between 2007 and 2010, the total net impact of investments in the southwestern region followed a declining trend, reducing to16.4% in

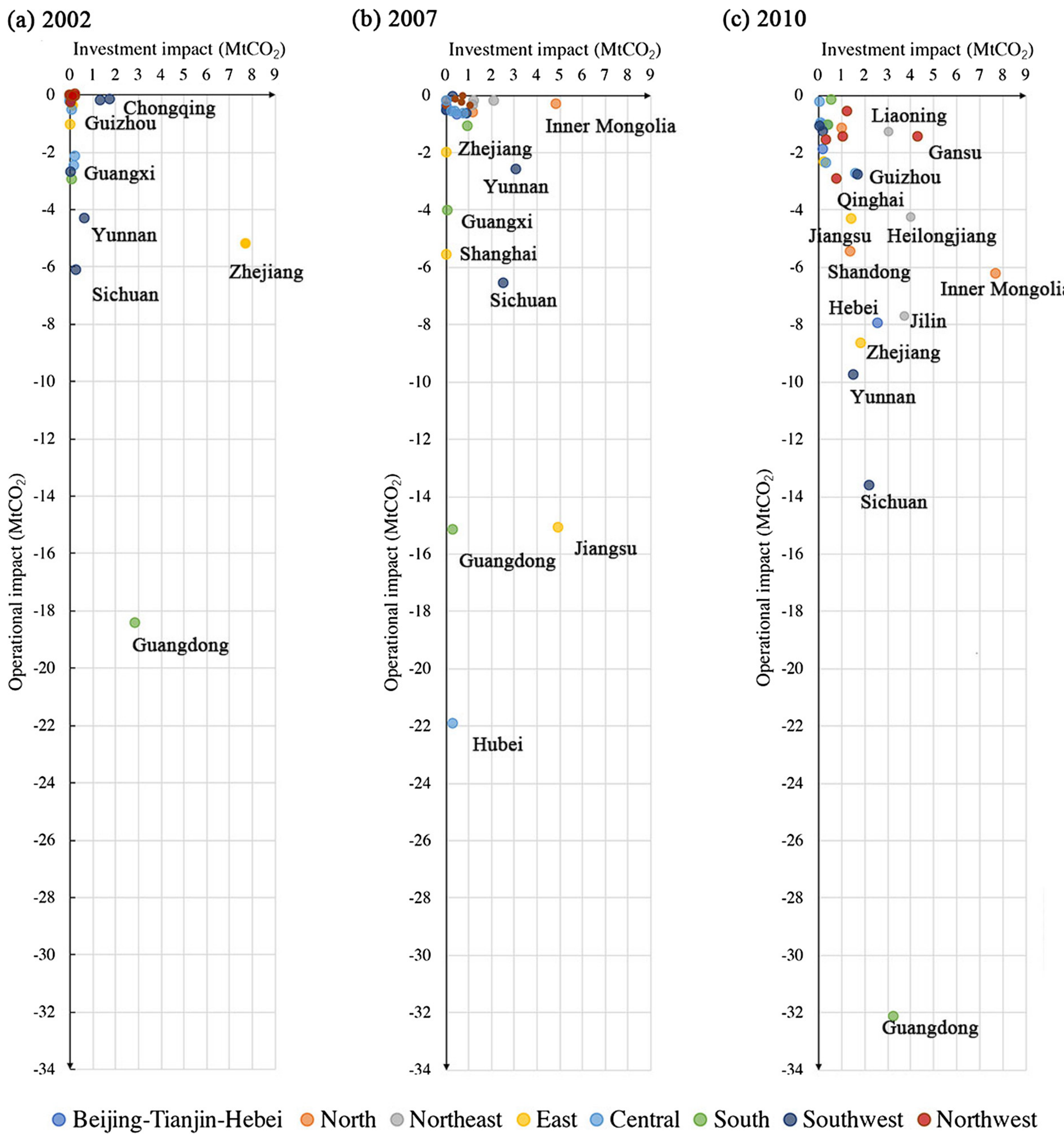


**Fig. 4.** A comparison of net $CO_2$ impacts between investment and operation.

2010 (6.78 Mt) compared to 2007 (5.67 Mt). Specifically, the net impact of investments in Guangxi reduced fastest, decreasing by 84.9% from 2007 to 2010. The net impact of investments in Yunnan and Sichuan also reduced sharply, decreasing from 11.5% to 50.7% from 2007 to 2010 respectively. At the absolute level, the net operational impact of NE in the southwestern region increased from 2002 (−13.6 Mt) to 2010 (−28.4 Mt). The net operational impact in Sichuan and Yunnan increased markedly, increasing by 121% and 125% from 2002 to 2010 respectively. By 2010, the magnitude impacts from NE investments in all southwestern provinces was significantly smaller than that of net operational impacts.

The net impact of investments in the northern, northwestern and northeastern regions increased from 2002 to 2010. Inner Mongolia increased fastest, followed by Gansu, Jilin, Liaoning, Hebei and Shandong. Substantial expansion was also seen in operational impacts in northern, northwestern and northeastern regions. Hebei's operational impacts grew fastest, to −7.94 Mt $CO_2$ in 2010 from −0.21 Mt in 2002, followed by Jilin, Inner Mongolia, Shandong, Liaoning and Qinghai. However, between 2007 and 2010, the magnitude of net investment impacts in Inner Mongolia and Gansu was considerably larger than net operational impacts. Managing the $CO_2$ impacts of NE infrastructure in these two regions will be important.

To better understand the impact of investments by different types of NE, Fig. 5 splits the impact of investments and operations in 30 provinces into NE technologies (for 2010). The net impact of investments reflects the geographic distribution of NE resources in China. Hydropower investment was an essential cause of emission growth in the southwestern and central regions, the most significant of which were in Sichuan and Guizhou, bringing a net $CO_2$ increase of 2.22 Mt and 1.69 Mt, respectively. Hydropower operation led to the largest emission reduction in Guangdong (−16.95 Mt), followed by Sichuan (−13.35 Mt) and Yunnan (−9.37 Mt). Nuclear power investment had positive effects on emissions in Zhejiang and Guangdong, leading to 1.76 Mt and 2.11 Mt of growth, respectively. Operational impacts of nuclear power played the most important role in emission decreases in Zhejiang and Guangdong, resulting in a 5.82 Mt and 13.86 Mt of growth, respectively.

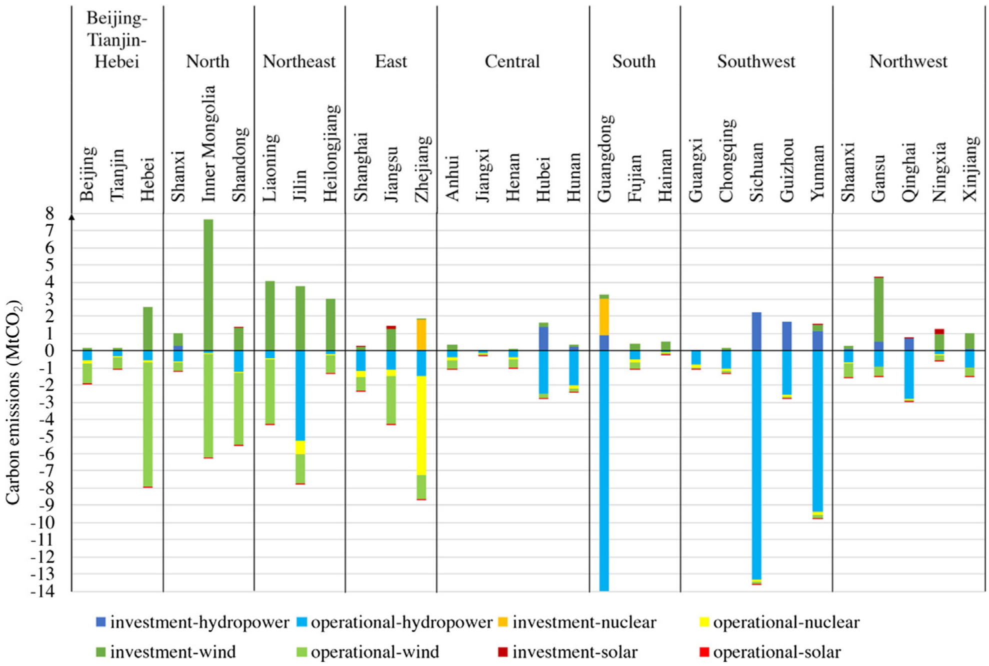


**Fig. 5.** Net investment and operational $CO_2$ impacts of NE for various energy types in 2010. Note: the net operational impact of NE in Guangdong is significantly larger than in other provinces. In order to present the results more clearly, we limited the y axis from 8 to −14. The total net operational impact of NE in Guangdong was −32.15 Mt. The net operational impact of hydropower, nuclear, wind and solar was −16.95 Mt, −13.86 Mt, −1.34 Mt and 0.00 Mt respectively.

Wind investments had significant impacts on emissions in Beijing-Tianjin-Hebei, northern, northeastern and northwestern regions. Specifically, wind investment induced the largest increase in emissions in Inner Mongolia (7.64 Mt), amounting to 99.6% of total emissions from investments. At the same time, wind operations had significant effects on reductions in Beijing-Tianjin-Hebei, northern, northeastern and northwestern regions, the most significant of which was Hebei (−7.24 Mt). The magnitude of impacts of wind investments outweighed that of operational impacts in several provinces. For instance, in Inner Mongolia and Gansu, the operational impact of wind led to a net $CO_2$ decrease of 6.04 Mt and 0.53 Mt respectively, while the wind investment resulted in a net $CO_2$ emission increase of 7.64 Mt and 3.73 Mt respectively.

Solar investments resulted in a net emission increase in the northwestern and eastern regions. Provincially, the largest impact of solar investment was Ningxia in 2010, followed by Qinghai and Jiangsu. The percentage of solar investment impacts compared to total investments in these provinces was more than 8%. The net decreases due to solar operation was smaller than the net increases due to solar investment in Jiangsu and Ningxia. These results show that controlling impacts of solar investment in the northwestern and eastern regions is important.

### *4.4. Spillover effects of non-fossil electricity investments*

Here we investigate spillover effects of NE investments on regional emissions. Fig. 6 shows that from 2002 to 2007, the eastern and southwestern regions have the highest net spillover effect. This is because investments (especially for hydropower and nuclear) are larger from 2002 to 2007, and require more intermediate goods from other provinces. NE investments in the eastern region increased all other regions' emissions, especially those of Beijing-Tianjin-Hebei and northern regions. This reflects the fact that infrastructure in the eastern region tends to use more intermediate goods. The transfer of investment impacts from the east to Beijing-Tianjin-Hebei and northern regions is reasonable in regards to geographic spatial distribution. Moreover, Beijing-Tianjin-Hebei and northern regions have close economic ties with the eastern region. Their industries follow the upstream industries of the eastern region, and large-scale demand of the eastern region provide the primary market for their products.

NE investments in the southwestern region generally increased intraregional emissions as it is a major region for the supply of primary natural resources, and many manufacturing industries are concentrated there. The southwestern region transfers the emission impacts of NE investments to the eastern region, implying that southwestern investments depend heavily on intermediate inputs from the eastern region. The southwestern region also transferred large impacts of NE investments to the central region, as the southwestern region is geographically close.

Spillover effects from investments for northern and northeastern regions maintained an increasing trend during 2002–2007 due to the growth of wind investments. Investments in the northeastern region had significant spillovers on emission increases in the Beijing-Tianjin-Hebei and northern regions, as they are geographically connected. Investments in the northern region also tend to drive purchasing of more goods from neighboring regions, thus, investments in the northern region drove emission increases in the Beijing-Tianjin-Hebei and northeastern regions.

With the rapid growth of wind investments, the spillover of NE investments in northeastern and northwestern regions nearly tripled from 2007 to 2010. Investments in the northeastern region had a large spillover on emissions in the northwestern region, as it has a strong base in traditional manufacturing industries.

## 5. Discussion

In this work, we applied MRIO models to account for the impacts of NE investments and operation in China's 30 provinces. The magnitude of increasing emissions from investments and the decreasing emissions from operation varied provincially. The net operational impact of NE in all southwestern and eastern provinces has been smaller than net impact of investments. Thus, southwestern and eastern regions could expand NE investments to reduce emissions. In their electricity system, the majority of investment impacts are from hydropower and nuclear. Hence, in order to maximize emission savings in NE development, the significant impact of expanding hydropower and nuclear is be worthy of attention. The impacts of investment are significant for northern, northeastern and northwestern regions, such that the magnitude of operational impacts in several provinces (e.g. Gansu and Inner Mongolia) was smaller than investment impacts. This is due to the fact that solar and wind infrastructure increased demand for manufacturing and construction sectors in northern, northeastern and northwestern

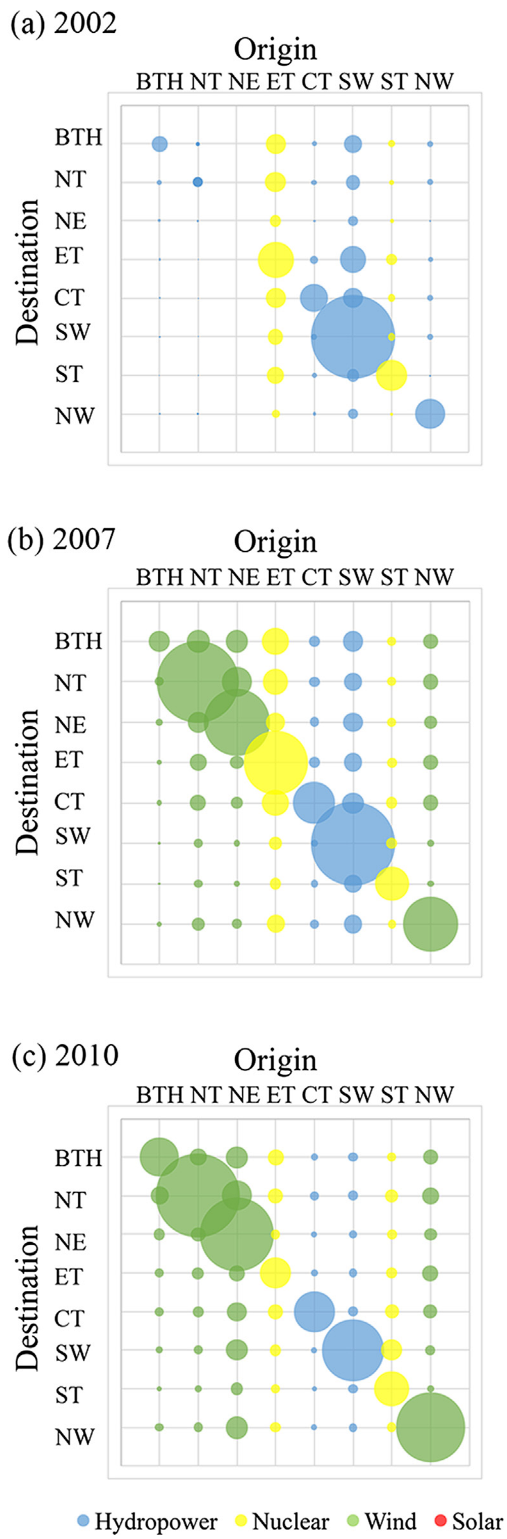


**Fig. 6.** The net spillover effect of NE investments (Unit: Mt $CO_2$). Note: "Origin" represents the region that externally affects other regions; "destination" represents the region affected by other regions' NE investments. Intraregional effect is shown on the diagonal, while interregional spillover effect is shown on the off-diagonal. The most important NE type in one region is indicated with corresponding colored bubbles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

provinces. Reducing emissions across the supply chain of wind and solar infrastructure may be effective in improving the total carbon impact of NE systems.

Identifying the pattern for the carbon impacts from NE investments appears to be particularly critical for reducing impacts and meeting policy targets. Our analysis shows that because inland regions use more domestic products, the intraregional effect of investments in these regions are large. Furthermore, a large spillover can be seen in the coastal eastern region, as it is located downstream in supply chains, with large backward linkages to the inland region. From the viewpoint of supply chains, if a region's NE infrastructure uses more domestic products, the intraregional effect should be larger. However, if this region uses more intermediate goods from other regions, the interregional spillover effects should be larger. As such, the pattern of regional impacts from NE investments also depends on the participation in supply chains.

The interregional transfer of investment impacts is related to the geographical proximity of provinces. The impact of investments tends to be transferred to neighbor regions, explaining the relationship to the central region from the southwestern region. The findings also provides evidence that investments in northern and northeastern regions have obvious carbon effects on Beijing-Tianjin-Hebei. Thus, spatial relationships could be a useful factor for analysis in NE policy. These findings show partial similarity to works of Yan et al. [105] and Meng et al. [106]. Feng et al. [107] provide a possible explanation for this transfer between neighboring regions, though they only focus on the distribution characteristics of carbon emissions. They suggest that since most products are homogenized and do not require long-distance transport, a region tends to use more intermediate goods from adjacent regions rather than more distant regions due to transportation costs. Similarly, NE infrastructure will stimulate emissions in surrounding regions through the construction of intermediate products, especially of those not suitable for long distance transportation.

China has relatively large economic disparities among regions. Generally, developing regions (e.g. north, northwest, northeast, southwest) have larger intraregional effects, while developed regions (e.g. east and Beijing-Tianjin-Hebei) show larger interregional spillover effects. Therefore, like the interregional transfer of $CO_2$ [108], the predominant pattern for spillover effects from NE investments is from developed regions to developing regions. This reflects the fact that developing regions play an important role in supplying energy and raw materials in the supply chains of NE infrastructure. Since manufacturing and construction industries contribute the most to NE infrastructure, from the point of view of production, improving technology and energy efficiency of manufacturing and construction industries in developing regions would be conductive to alleviating the carbon impact of NE investments.

Significant interregional transfers of carbon stimulated by NE investments were found between the northeast region to Beijing-Tianjin-Hebei and between the southwest region to the east. This provides evidences of another pattern of spillover effects: NE investments in developing regions also can affect developed regions' emissions. This is as a result of intermediate products utilized for NE infrastructure can require higher levels of technology and developed regions can provide such intermediate products. Thus, one possible approach for developing regions in reducing the carbon impact of NE investments is to strengthen interregional collaboration with developed regions and promote technology transfers.

These estimates for the carbon impacts of NE investments provide robust arguments for the discussion of the preferable investment pattern of the electricity system. The results show that the carbon payback time could be in the order of one year and hence that investment impacts are negligible relative to operational impacts. The results also emphasize that China could determine the provincial carbon impact of investments based on consumption-accounting principles and reallocate emission responsibilities of to the benefiting regions. Moreover, we developed a hybrid MRIO model, which integrates NE operational data in physical units into the MRIO model in monetary units. This hybrid MRIO model improves the reliability of MRIO analyses by avoiding the disaggregation of MRIO tables. This framework can be used for other countries. Future work could also use a similar framework for analyzing the provincial influence of NE generators on other important factors such as water, and applied to energy-water nexus studies similar to Duan and Chen [109]. This could be extended to geographically explicit energy-water-climate studies such as Behrens et al. [110].

Since investments in solar during 2002–2010, was small, the associated emissions were also small. Solar investment increased considerably between 2011 and 2016, however, due to limited data, we did not analyze solar power investment after 2010. The emissions impact of solar investment in China and across provinces will need further analysis as data becomes available. Moreover, it should be noted that, due to data limitations, we only consider emissions from fossil fuel combustion and cement production, as previous literature highlights that these are the dominant emitters. However, as discussed in Wiedmann et al. [12], to further assess the impact of NE infrastructure, emissions from plastics could be included in the future.

## 6. Conclusions

The recent trend toward developing non-fossil electricity at a large scale has prompted concerns of increased emissions from infrastructure development. With the support of several MRIO models, this study used a counterfactual scenario to estimate the carbon impacts of non-fossil electricity investment and operational impacts in 30 provinces from 2002 to 2010. We distinguish intraregional and interregional spillover effects.

Our results confirmed that non-fossil electricity investments drove $CO_2$ emissions during 2002–2010, with a net increase of 16.21 Mt in 2002, 28.71 Mt in 2007 and 46.29 Mt in 2010. However, the total operational impact of non-fossil electricity played an important role in mitigating emissions in China across the studied periods. The net $CO_2$ emission decreases in 2002, 2007 and 2010 reached 48.84 Mt, 81.83 Mt and 129.48 Mt. Investment in hydropower and nuclear had larger effects on emissions during 2002–2007, especially in Guangdong, eastern and southwestern provinces. The magnitude of impacts for non-fossil electricity investments in these provinces has been smaller than the net operational impacts. Wind investment had a large impact on emissions during 2007–2010, especially in the northern, northeastern and northwestern regions. Emission reductions from operation were offset by emission increases from non-fossil electricity investments in several northern, northeastern and northwestern provinces (e.g. Gansu and Inner Mongolia). Significant differences were observed between intraregional and interregional spillover effects between regions. The developed eastern region has a larger interregional spillover effect, while developing regions, such as southwest, north, northeast and northwest, show larger intraregional effects. Regions with large-scale non-fossil electricity investments tend to transfer emissions from non-fossil electricity investments to neighboring regions.

## Appendix A

See Tables A1–A4.

**Table A1**
Sector classifications for the Chinese economy.

| Code | Sector |
|---|---|
| 1 | Agriculture |
| 2 | Mining |
| 3 | Food and Tobacco |
| 4 | Textile |
| 5 | Processing of Timber and Furniture |
| 6 | Paper and Paper Products |
| 7 | Petroleum Refining and Coking |
| 8 | Chemical |
| 9 | Non-metallic Mineral Products |
| 10 | Smelting and Pressing of Metals |
| 11 | Metal Products |
| 12 | General Equipment |
| 13 | Transport Equipment |
| 14 | Electric Machinery and Equipment |
| 15 | Electronic Equipment |
| 16 | Mearing Instruments and Machinery of Cultural Activity and Office Work |
| 17 | Other Manufacturing |
| 18 | Electricity |
| 19 | Construction |
| 20 | Transportation |
| 21 | Services |

**Table A2**
Region classifications.

| Region | Province that included in each region |
|---|---|
| Beijing-Tianjin-Hebei (BTH) | Beijing, Tianjin and Hebei |
| North (NT) | Hebei, Shanxi, Inner Mongolia and Shandong |
| Northeast (NE) | Liaoning, Jilin and Heilongjiang |
| East (ET) | Jiangsu, Shanghai and Zhejiang |
| Central (CT) | Henan, Anhui, Hunan, Hubei and Jiangxi |
| South (ST) | Fujian, Guangdong and Hainan |
| Southwest (SW) | Sichuan, Chongqing, Guizhou, Yunnan and Guangxi |
| Northwest (NW) | Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang |

**Table A3**
Investment structure of electricity technologies (%).

| Sector | Thermal | Hydro | Nuclear | Wind | Solar |
|---|---|---|---|---|---|
| AGR | 0 | 0 | 0 | 0 | 0 |
| MC | 0 | 0 | 0 | 0 | 0 |
| FD | 0 | 0 | 0 | 0 | 0 |
| TEX | 0 | 0 | 0 | 0 | 0 |
| TF | 0 | 0 | 0 | 0 | 0 |
| PP | 0 | 0 | 0 | 0 | 0 |
| PC | 0 | 0 | 0 | 0 | 0 |
| CHE | 0 | 0 | 0 | 0 | 0 |
| NMP | 0 | 0 | 0 | 0 | 0 |
| SPM | 0 | 0 | 0 | 0 | 0 |
| MP | 0 | 0 | 0 | 5 | 3 |
| GE | 29 | 28 | 55 | 38 | 40 |
| TE | 0 | 2 | 0 | 5 | 0 |
| EME | 0 | 0 | 0 | 0 | 0 |
| EE | 4 | 7 | 15 | 5 | 12 |
| IM | 0 | 0 | 0 | 0 | 0 |
| OM | 0 | 0 | 0 | 0 | 0 |
| ELE | 0 | 0 | 0 | 0 | 0 |
| CON | 55 | 35 | 25 | 15 | 13 |
| TRA | 6 | 8 | 0 | 12 | 8 |
| SE | 6 | 20 | 5 | 20 | 24 |
| Total | 100 | 100 | 100 | 100 | 100 |

**Table A4**
Regional carbon intensity of electricity installation ($MtCO_2/GW$).

| | Thermal | | | Hydro | | | Nuclear | | | Wind | | Solar |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2002 | 2007 | 2010 | 2002 | 2007 | 2010 | 2002 | 2007 | 2010 | 2007 | 2010 | 2010 |
| Beijing | | 0.59 | 1.07 | | | | | | | | 2.65 | |
| Tianjin | 0.36 | 0.80 | 0.39 | | | | | | | | 2.27 | |
| Hebei | 0.70 | 0.70 | 1.77 | 2.12 | | | | | | 3.01 | 1.97 | |
| Shanxi | 0.68 | 0.71 | 0.73 | | | 1.60 | | | | | 2.08 | |
| Inner Mongolia | 1.20 | 1.56 | 0.59 | 2.00 | | 2.47 | | | | 3.48 | 1.98 | |
| Shandong | 0.47 | 0.44 | 1.33 | 2.18 | 1.77 | 1.38 | | | | 3.55 | 2.10 | 3.20 |
| Liaoning | 0.36 | 1.64 | 0.52 | | | | | | | 4.55 | 3.67 | |
| Jilin | 1.08 | 1.14 | 1.13 | | 1.82 | 1.39 | | | | 4.08 | 5.03 | |
| Heilongjiang | 0.31 | 1.26 | 1.10 | 2.67 | 1.75 | | | | | 4.38 | 4.98 | |
| Shanghai | 0.79 | 1.67 | 0.24 | | | | | | | | 2.61 | 2.48 |
| Jiangsu | 0.99 | 1.61 | 0.29 | 1.58 | | | | 3.62 | | 4.07 | 2.19 | 2.50 |
| Zhejiang | 0.41 | 0.37 | 0.65 | 1.62 | | 1.70 | 5.71 | | 3.56 | 3.07 | 2.76 | |
| Anhui | 0.74 | 0.73 | 1.70 | | 1.86 | | | | | | 2.54 | |
| Jiangxi | 0.89 | 0.84 | 0.64 | 1.38 | | | | | | | | |
| Henan | 0.61 | 0.66 | 0.88 | | 2.87 | | | | | 5.21 | 3.04 | |
| Hubei | 0.81 | 0.62 | 0.57 | 3.21 | 0.66 | 2.47 | | | | 5.13 | 3.30 | |
| Hunan | 0.86 | 0.87 | 0.79 | 1.83 | 2.08 | 0.89 | | | | | 3.76 | |
| Fujian | 0.50 | 0.31 | 0.22 | 2.46 | 1.97 | 1.75 | | | | 3.67 | 2.69 | |
| Guangdong | 0.50 | 0.38 | 0.32 | 1.42 | | 0.89 | 3.07 | | 2.44 | 3.99 | 2.00 | |
| Hainan | 0.62 | 0.52 | 0.41 | 2.86 | 2.85 | 1.54 | | | | | 4.13 | |
| Guangxi | 0.94 | 0.64 | 0.60 | 2.04 | 0.65 | 0.67 | | | | | | |
| Chongqing | 1.60 | | 1.09 | | | 1.19 | | | | | 3.95 | |
| Sichuan | 1.56 | 0.82 | 0.74 | 2.13 | 1.58 | 1.26 | | | | | | |
| Guizhou | 0.78 | 0.60 | 0.91 | | 2.56 | 1.00 | | | | | | |
| Yunnan | 1.60 | 1.42 | 0.78 | 2.46 | 1.66 | 0.84 | | | | | 2.05 | 3.67 |
| Shaanxi | 1.44 | 0.43 | 0.51 | 2.84 | | 0.90 | | | | | 3.77 | |
| Gansu | 1.09 | 0.65 | 0.38 | 2.26 | 2.11 | 2.29 | | | | 5.21 | 2.30 | 4.27 |
| Qinghai | 0.80 | 1.46 | 0.72 | 1.69 | 2.59 | 2.00 | | | | | | 5.64 |
| Ningxia | 0.68 | 1.78 | 1.43 | | | | | | | 5.25 | 3.33 | 5.54 |
| Xinjiang | 0.77 | 1.04 | 1.11 | 1.93 | 2.53 | 1.24 | | | | 5.05 | 3.32 | |

## References


[1] Intergovernmental Panel on Climate Change (IPCC). Climate change 2001: impacts, adaptation and vulnerability. UK: Report of the working group II, Cambridge University Press; 2001. pp. 967.

[2] United Nations Framework on Climate Change (UNFCCC). In: Annual Conference of Parties, COP21, Paris, France, 7–8 December 2015. Adoption of the Paris Agreement; 2015. < http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf, accessed 20th December 2015 > .

[3] Tambo E, Duo-quan W, Zhou X-N. Tackling air pollution and extreme climate changes in China: implementing the Paris climate change agreement. Environ Int 2016;95:152–66.

[4] Chen A, Groenewold N. Emission reduction policy: a regional economic analysis for China. Econ Model 2015;51:136–52.

[5] Hu A-G. The Five-Year Plan: a new tool for energy saving and emission reduction in China. Adv Clim Change Res 2016;7:222–8.

[6] Wu J, Kang Z, Zhang N. Carbon emission reduction potentials under different polices in Chinese cities: a scenario based analysis. J Clean Prod 2017;161:1226–36.

[7] Yang XJ, Hu H, Tan T, Li J. China's renewable energy goals by 2050. Environ Develop 2016;20:83–90.
[8] National Development and Reform Commission (NDRC). The 13th Five-Year Plan for Economic and Social Development of the People's Republic of China 2016-2020. Compilation and Translation Bureau, Central Committee of the Communist Party of China Beijing, China; 2016. < http://en.ndrc.gov.cn/newsrelease/201612/P020161207645765233498.pdf > .
[9] Dai H, Xie X, Xie Y, Liu J, Masui T. Green growth: the economic impacts of large-scale renewable energy development in China. Appl Energy 2016;162:435–49.
[10] Bloomberg New Energy Finance (BNEF). Energy Investment End of Year 2016; 2017. < https://about.bnef.com/clean-energy-investment/ > .
[11] Behrens P, Rodrigues JFD, Bras T, Silva. Environmental, economic, and social impacts of feed-in tariffs: a Portuguese perspective 2000–2010. Appl Energy 2016;173:309–19.
[12] Wiedmann TO, Suh S, Feng K, Lenzen M, Acquaye A, Scott K, et al. Application of hybrid life cycle approaches to emerging energy technologies – the case of wind power in UK. Environ Sci Technol 2011;45:5900–7.
[13] Lindner S, Legault J, Guan D. Disaggregating input-output models with incomplete information. Econ Syst Res 2012;24:329–47.
[14] Qi T, Zhang X, Karplus JV. The energy and $CO_2$ emissions impact of renewable energy development in China. Energy Policy 2014;68:60–9.
[15] Long X, Naminse EY, Du J, Zhuang J. Nonrenewable energy, renewable energy, carbon dioxide emissions and economic growth in China from 1952 to 2012. Renew Sustain Energy Rev 2015;52:680–8.
[16] Li Z, Jia X, Foo DCY, Tan RR. Minimizing carbon footprint using pinch analysis: the case of regional renewable electricity planning in China. Appl Energy 2016;184:1051–62.
[17] Mittal S, Dai H, Fujimori S, Masui T. Bridging greenhouse gas emissions and renewable energy deployment target: comparative assessment of China and India. Appl Energy 2016;166:301–13.
[18] Wu J, Albrecht J, Fan Y, Xia Y. The design of renewable support schemes and $CO_2$ emissions in China. Energy Policy 2016;99:4–11.
[19] Duan H. Emissions and temperature benefits: The role of wind power in China. Environ Res 2017;152:342–50.
[20] Ito K. $CO_2$ emissions, renewable and non-renewable energy consumption, and economic growth: evidence from panel data for developing countries. Int Econ 2017;151:1–6.
[21] Yuan R, Rodrigues JFD, Behrens P. Impact of non-fossil electricity on the carbon emissions embodied in China's exports. J Clean Prod 2018;192:582–96.
[22] Cong. An optimization model for renewable energy generation and its application in China: a perspective of maximum utilization. Renew Sustain Energy Rev 2013;17:94–103.
[23] Zhang M, Zhou D, Ding H, Jin J. Biomass power generation investment in China: a real options evolution. Sustainability 2016;8:563. https://doi.org/10.3390/su8060563.
[24] Perera ATD, Attalage RA, Perera KKCK, Dassanayake VPC. Designing standalone hybrid energy systems minimizing initial investment, life cycle cost and pollutant emission. Energy 2013;54:220–30.
[25] Hertwich EG, Gibon T, Bouman EA, Arvesen A, Suh S, Heath GA, et al. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. Proc Natl Acad Sci 2015;112:6277–82.
[26] Qu X, Yuan Z, Peng T, Sun Z, Zhou S. The low-carbon transition toward sustainability of regional coal-dominated energy consumption structure: a case of Hebei Province in China. Sustainability 2017;9:1184. https://doi.org/10.3390/su9071184.
[27] Yahoo M, Othman J. Employing a CGE model in analyzing the environmental and economy-wide impacts of $CO_2$ emission abatement policies in Malaysia. Sci Total Environ 2017;584–585:234–43.
[28] Yamazaki M, Takeda S. A computable general equilibrium assessment of Japan's nuclear energy policy and implications for renewable energy. Environ Econ Policy Stud 2017;19:537–54.
[29] Ulrich P, Distelkamp M, Lehr U. Employment effects of renewable energy expansion on regional level-first results of a model-based approach for Germany. Sustainability 2012;4:227–43.
[30] Rodrigues JFD, Marques A, Wood R, Tukker A. A network approach for assembling and linking input–output models. Econ Syst Research 2016;28:518–38.
[31] Lee D, Lee D, Chiu L. Biohydrogen development in United States and in China: an input-output model study. Hydrogen Energy 2011;36:14238–44.
[32] Caldes N, Varela M, Santamaria M, Saez R. Economic impact of solar thermal electricity deployment in Spain. Energy Policy 2009;37:1628–36.
[33] De Arce R, Mahia R, Medina E, Escribano G. A simulation of the economic impact of renewable energy development in Morocco. Energy Policy 2012;46:335–45.
[34] Lehr U, Lutz C, Edler D. Green jobs? Economic impacts of renewable energy in Germany. Energy Policy 2012;47:358–64.
[35] Markaki M, Belegri-Roboli A, Michaelides P, Mirasgedis S, Lalas DP. The impact of clean energy investments on the Greek economy: an input-output analysis (2010–2020). Energy Policy 2013;57:263–75.
[36] Chun D, Woo C, Seo H, Chuang Y, Hong S, Kim J. The role of hydrogen energy development in the Korean economy: an input-output analysis. Int J Hydrogen Energy 2014;39:7627–33.
[37] Varela-Vazquez P, Sanchez-Carreira MD. Socioeconomic impact of wind energy on peripheral regions. Renew Sustain Energy Rev 2015;50:982–90.
[38] Lehr U, Nitsch J, Kratzat M, Lutz C, Edler D. Renewable energy and employment in Germany. Energy Policy 2008;36:108–17.
[39] Tourkolias C, Mirasgedis S. Quantification and monetization of employment benefits associated with renewable energy technologies in Greece. Renew Sustain Energy Rev 2011;15:2876–86.
[40] Oliveira C, Coelho D, Pereira da Silva P, Antunes HC. How many job can the RES-E sectors generate in Portuguese context? Renew Sustain Energy Rev 2013;21:444–55.
[41] Simas M, Pacca S. Assessing employment in renewable energy technologies: A case study for wind power in Brazil. Renew Sustain Energy Rev 2014;31:83–90.
[42] Okkonen L, Lehtonen O. Socio-economic impacts of community wind power projects in Northern Scotland. Renew Energy 2016;85:826–33.
[43] Ortega M, Del Rio P, Ruiz P, Thiel C. Employment effects of renewable electricity deployment. A novel methodology. Energy 2015;91:940–51.
[44] Dvořák P, Martinát S, Horst van der D, Frantál B, Turečková K. Renewable energy investment and job creation; a cross-sectoral assessment for the Czech Republic with reference to EU benchmarks. Renew Sustain Energy Rev 2017;69:360–8.
[45] Garrett-Peltier H. Green versus brown: Comparing the employment impacts of energy efficiency, renewable energy, and fossil fuels using an input-output model. Econ Model 2017;61:430–47.
[46] Madlener R, Koller M. Economic and $CO_2$ mitigation impacts of promoting biomass heating systems: an input-output study for Vorarlberg, Austria. Energy Policy 2007;35:6021–35.
[47] Ritchie J, Dowlatabadi H. Understanding the shadow impacts of investment and divestment decisions: adapting economic input-output models to calculate biophysical factors of financial returns. Ecol Econ 2014;106:132–40.
[48] Choi J, Morrison D, Hallinan PK, Brecha JR. Economic and environmental impacts of community-based residential building energy efficiency investment. Energy 2014;78:877–86.
[49] Choi J, Bakshi RB, Hubacek K, Nader J. A sequential input-output framework to analyze the economic and environmental implications of energy policies: gas taxes and fuel subsidies. Appl Energy 2016;184:830–9.
[50] Medina A, Camara A, Monrobel J. Measuring the socioeconomic and environmental effects of energy efficiency investment for a more sustainable Spanish economy. Sustainability 2016;8:1039.
[51] Lucchesi A, Pereda PC, Garcia CP, Palialol BT. Long-term effects of structural changes in the Brazilian electricity matrix. Clean Technol Environ Policy 2017;19:1589–605.
[52] Cai W, Mu Y, Wang C, Chen J. Distributional employment impacts of renewable and new energy – a case study of China. Renew Sustain Energy Rev 2014;39:1155–63.
[53] Yuan R, Behrens P, Arnold T, Rodrigues JFD. Carbon overhead: The impact of the expansion in low-carbon electricity in China 2015–2040. Energy Policy 2018;119:97–104.
[54] Danial M, Wood R, Rodrigues JFD. A note on the magnitude of the feedback effect in environmentally extended multi-region input-output tables. J Ind Ecol 2017;22:532–9.
[55] Usubiaga A, Acosta-Fernandez J, McDowall W, Li FGN. Exploring the macro-scale $CO_2$ mitigation potential of photovoltaics and wind energy in Europe's energy transition. Energy Policy 2017;104:203–13.
[56] Crawford RH, Bontinck P, Stephan A, Wiedmann T, Yu M. Hybrid life cycle inventory methods – a review. J Clean Prod 2018;172:1273–88.
[57] Hondo H, Moriizumi Y. Employment creation potential of renewable power generation technologies: a life cycle approach. Renew Sustain Energy Rev 2017;79:128–36.
[58] Zhang B, Chen ZM, Xia XH, Xu XY, Chen YB. The impact of domestic trade on China's regional energy uses: a multi-regional input-output modeling. Energy Policy 2013;63:1169–81.
[59] Zafrilla JE, Cadarso MA, Monsalve F, de la Rua C. How carbon-friendly is nuclear energy? A hybrid MRIO-LCA Model of a Spanish Facility. Environ Sci Technol 2014;48:14103–11.
[60] Su B, Ang BW. Input–output analysis of $CO_2$ emissions embodied in trade: the effects of spatial aggregation. Ecol Econ 2010;70:10–8.
[61] Matumoto N, Hondo H. Analysis on employment effects of the introduction of renewable energy technologies using an extended input-output table. J Japan Inst Energy 2011;90:258–67.
[62] Rocco MV, Lucchio AD, Colombo E. Exergy Life Cycle Assessment of electricity production from Waste-to-Energy technology: a Hybrid Input-Output approach. Appl Energy 2017;194:832–44.
[63] Li X, Feng K, Siu YL, Hubacek K. Energy-water nexus of wind power in China: the balancing act between $CO_2$ emissions and water consumption. Energy Policy 2012;45:440–8.
[64] Guevara Z, Rodrigues FDJ. Structural transition and energy use: a decomposition analysis of Portugal 1995–2010. Econ Syst Res 2016;28:202–23.
[65] Zhang C, Zhong L, Liang S, Sanders TK, Wang J, Xu M. Virtual scarce water embodied in inter-provincial electricity transmission in China. Appl Energy 2017;187:438–48.
[66] Rodrigues JFD, Lorena A, Costa IS, Ferrão P. An input-output model of extended producer responsibility. J Ind Ecol 2016;20:1273–83.
[67] Lindner S, Legault J, Guan D. Disaggregating the electricity sector of China's input-output table for improved environmental life-cycle assessment. Econ Syst Res 2013;25:300–20.
[68] Lindner S, Guan D. A hybrid–unit energy Input-Output model to evaluate embodied energy and life cycle emission for China's economy. J Ind Ecol 2014;18:201–11.
[69] Wang Y. An industrial ecology virtual framework for policy making in China. Econ Syst Res 2017;29:252–74.
[70] Shi MJ, Zhang ZY. Multi-regional Input-output Model and Inter-Regional Economic Linkages. Beijing: Science Publishing House; 2012. in Chinese.
[71] Liu W, Chen J, Tang Z, Liu H, Han D, Li F. China's 30 Provincial Multi-Regional

Input-output Table Theory and Practice in 2007. Beijing: China Statistics Press; 2012. in Chinese.
[72] Liu W, Tang Z, Chen J, Yang B. China's 30 Provincial Multi-Regional Input-output Table Theory and Practice in 2010. Beijing: China Statistics Press; 2014. in Chinese.
[73] Shan Y, Guan D, Liu J, Mi Z, Liu Z, Liu J, et al. Methodology and applications of city level $CO_2$ emissions accounts in China. J Clean Prod 2017;161:1215–25.
[74] Intergovernmental Panel on Climate Change (IPCC). 2006 IPCC Guideline for National Greenhouse Gas Inventories. Institute for Global Environmental Strategies (IGES), Hayama, Japan; 2006.
[75] National Bureau of Statistics of China (NBS). 2002 China Energy Statistical Yearbook. Beijing: China Statistics Press; 2003. in Chinese.
[76] National Bureau of Statistics of China (NBS). 2007 China Energy Statistical Yearbook. Beijing: China Statistics Press; 2008. in Chinese.
[77] National Bureau of Statistics of China (NBS). 2010 China Energy Statistical Yearbook. Beijing: China Statistics Press; 2011. in Chinese.
[78] Zhang Z, Guo J, Hewings GJD. The effects of direct trade within China on regional and national $CO_2$ emissions. Energy Econ 2014;46:161–75.
[79] National Bureau of Statistics of China (NBS). 2002 Provincial Statistical Yearbook. Beijing: China Statistics Press; 2003. in Chinese.
[80] National Bureau of Statistics of China (NBS). 2007 Provincial Statistical Yearbook. Beijing: China Statistics Press; 2008. in Chinese.
[81] National Bureau of Statistics of China (NBS). 2010 Provincial Statistical Yearbook. Beijing: China Statistics Press; 2011. in Chinese.
[82] National Bureau of Statistics of China (NBS). 2002 China Statistical Yearbook. Beijing: China Statistics Press; 2003. in Chinese.
[83] National Bureau of Statistics of China (NBS). 2007 China Statistical Yearbook. Beijing: China Statistics Press; 2008. in Chinese.
[84] National Bureau of Statistics of China (NBS). 2010 China Statistical Yearbook. Beijing: China Statistics Press; 2011. in Chinese.
[85] National Development and Reform Commission (NDRC), 2011. P. R. China National Development and Reform Commission (NDRC) Guidelines for Provincial Greenhouse Gas Inventories (Chinese document). < http://en.ndrc.gov.cn > .
[86] Emissions Database for Global Atmospheric Research (EDGAR), 2016. CO2 time series 1990–2015 per region/country emissions. < http://edgar.jrc.ec.europa.eu > .
[87] Energy Information Administration (EIA). International Energy Outlook 2017; 2017. < https://www.eia.gov, accessed November 2017 > .
[88] Carbon Dioxide Information Analysis Center (CDIAC). Fossil-fuel CO2 emissions; 2015. < http://cdiac.ornl.gov/trends/emis/meth_reg.html > .
[89] British Petroleum (BP). BP 2015 data of the BP Statistical Review of World Energy; 2016. < http://www.bp.com/en/global/corporate/about-bp/energy-economics/statisticalreview-of-world-energy.html > .
[90] China Electric Power Yearbook Editorial Board (CEPYEB). China electric power yearbook 2002. Beijing: China Electric Power Press; 2003. in Chinese.
[91] China Electric Power Yearbook Editorial Board (CEPYEB). China electric power yearbook 2007. Beijing: China Electric Power Press; 2008. in Chinese.
[92] China Electric Power Yearbook Editorial Board (CEPYEB). China electric power yearbook 2010. Beijing: China Electric Power Press; 2011. in Chinese.
[93] China Electricity Council (CEC). Annual development report of China's power sector 2003. Beijing; 2003 [in Chinese].
[94] China Electricity Council (CEC). Annual development report of China's power sector 2008. Beijing; 2008 [in Chinese].
[95] China Electricity Council (CEC). Annual development report of China's power sector 2011. Beijing; 2011 [in Chinese].
[96] National Energy Technology Laboratory. Cost and Performance Baseline for Fossil Energy Plants: vol. 1: bituminous Coal and Natural Gas to Electricity, DOE/NETL-2010/1397 (Rev. 2); 2010. < https://www.netl.doe.gov > .
[97] State Grid of China (SGC). Annual report of power market transactions 2007. Beijing: China Electricity Council; 2008. in Chinese.
[98] State Grid of China (SGC). Annual report of power market transactions 2010. Beijing: China Electricity Council; 2011. in Chinese.
[99] Haapala KR, Prempreeda P. Comparative life cycle assessment of 2.0 MW wind turbines. Int J Sustain Manuf 2014;3:170–85.
[100] Comodi G, Bevilacqua M, Caresana F, Paciarotti C, Pelagalli L, Paola V. Life cycle assessment and energy-$CO_2$-economic payback analyses of renewable domestic hot water systems with unglazed and glazed solar thermal panels. Appl Energy 2016;164:944–55.
[101] Tahara K, Kojima T, Inaba A. Evaluation of $CO_2$ payback time of power plants by LCA. Energy Convers Manage 1997;38:S615–20.
[102] Bush R, Jacques DA, Scott K, Barrett J. The carbon payback of micro-generation: an integrated hybrid input-output approach. Appl Energy 2014;119:85–98.
[103] Atse L, Wilfried GJHMS, Andre' PCF, Schropp REI. Re-assessment of net energy production and greenhouse gas emissions avoidance after 40 years of photovoltaics development. Nat Commun 2016;7:13728.
[104] Zou H, Du H, Broadstock CD, Guo J, Gong Y, Mao G. China's future energy mix and emissions reduction potential: a scenario analysis incorporating technological learning curves. J Clean Prod 2016;112:1475–85.
[105] Yan D, Lei Y, Li L, Song W. Carbon emission efficiency and spatial clustering analyses in China's thermal power industry: evidence from the provincial level. J Clean Prod 2017;156:518–27.
[106] Meng B, Wang J, Andrew R, Xiao H, Xue J, Peters GP. Spatial spillover effects in determining China's regional $CO_2$ emissions growth: 2007–2010. J Clean Prod 2017;63:161–73.
[107] Feng K, Hubacek K, Sun L, Liu Z. Consumption-based $CO_2$ accounting of China's mega cities: the case of Beijing, Tianjin, Shanghai and Chongqing. Ecol Ind 2014;47:26–31.
[108] Liu Z, Davis SJ, Feng KH, Hubacek K, Liang S, Anadon DL, et al. Targeted opportunities to address the climate-trade dilemma in China. Nat Clim Change 2015;6:720201–6.
[109] Duan C, Chen B. Energy-water nexus of internatiaonl energy trade of China. Appl Energy 2016;194:725–34.
[110] Behrens P, van Vliet MTH, Nanninga T, Walsh B, Rodrigues JFD. Climate change and the vulnerability of electricity generation to water stress in the European Union. Nat Energy 2017;2:17114.